CO_2 and Vertical Mixing

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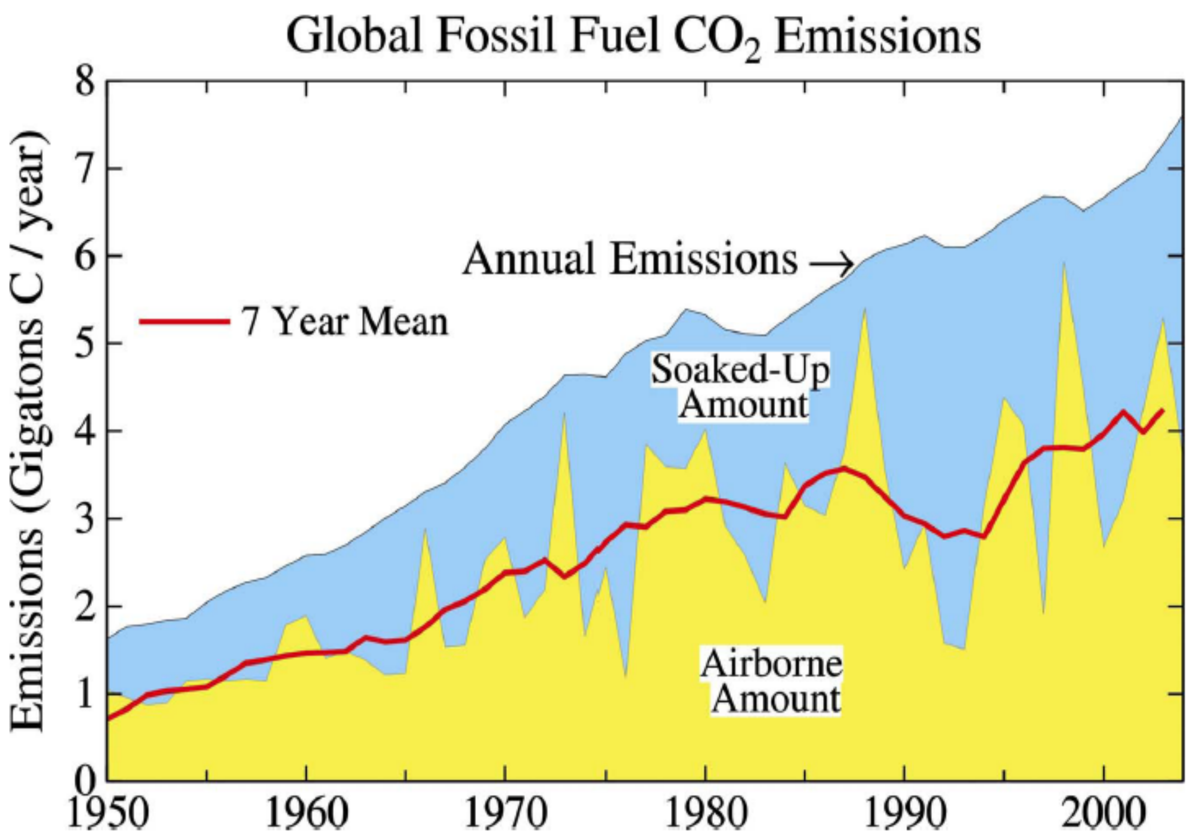
Holy Grail: Where is the Elusive Carbon Sink?

- **Only half of the CO_2 produced by human activities is remaining in the atmosphere**
- **Where are the *sinks* that are absorbing over 40% of the CO_2 that we emit?**
  - **Land or ocean?**
  - **Eurasia/North America?**
- **Why does CO_2 buildup vary dramatically with nearly uniform emissions?**
- **How will CO_2 sinks respond to climate change?**



Global fossil fuel CO_2 emissions with division into portions that remain airborne or are soaked up by the ocean and land.

Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

Fate of Anthropogenic CO_2 Emissions (2000-2009)

1.1±0.7 PgC y^{-1}

7.7±0.5 PgC y^{-1}

+

4.1±0.1 PgC y^{-1}

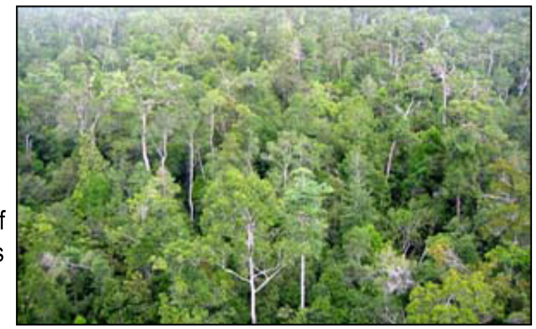
47%

Radiatively active

2.4 PgC y^{-1}

27%

Calculated as the residual of all other flux components



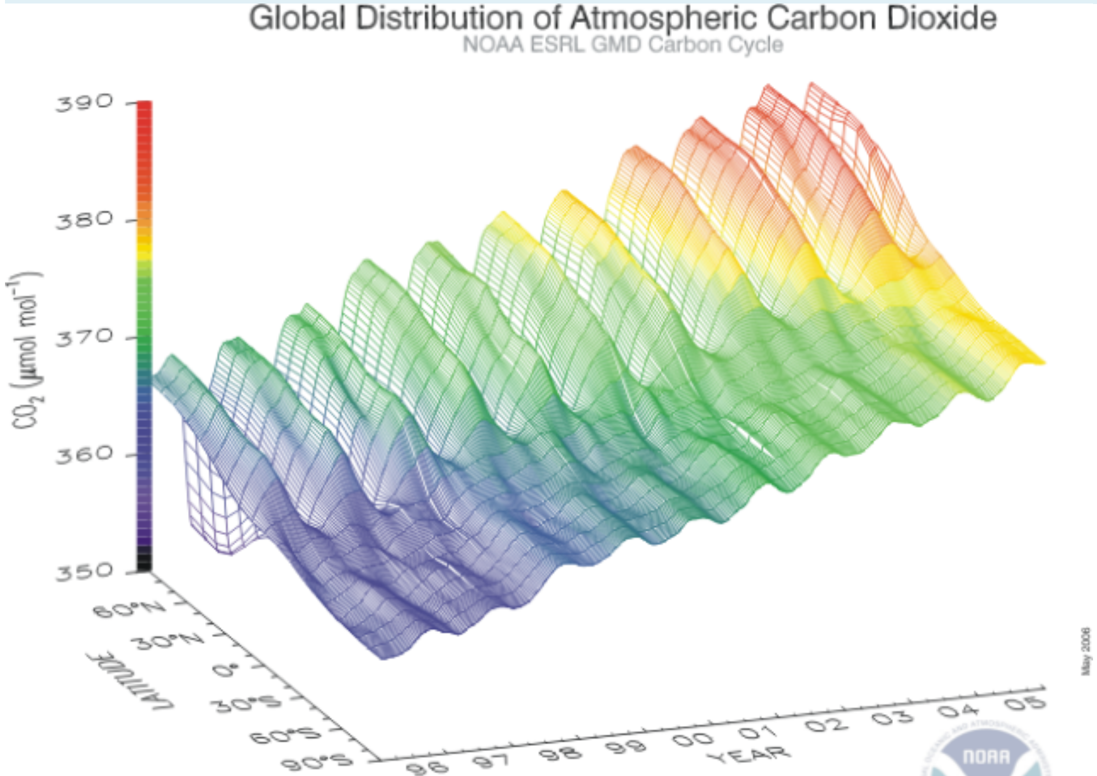
26%

2.3±0.4 PgC y^{-1}

Average of 5 models

Global Carbon Project 2010; Updated from Le Quéré et al. 2009, Nature Geoscience; Canadell et al. 2007, PNAS

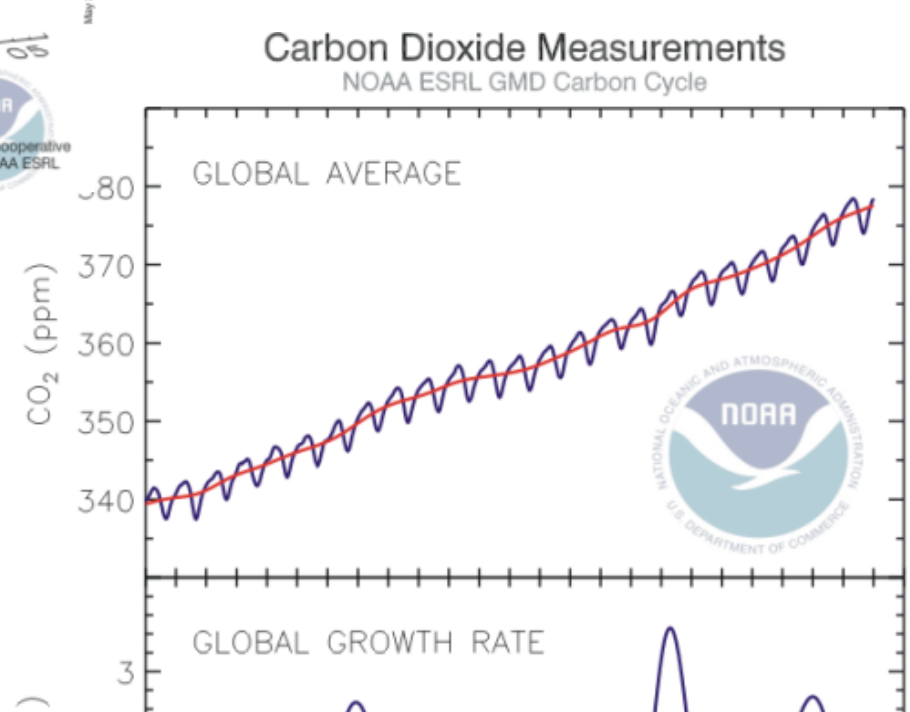
CO2 Distribution in the atmosphere



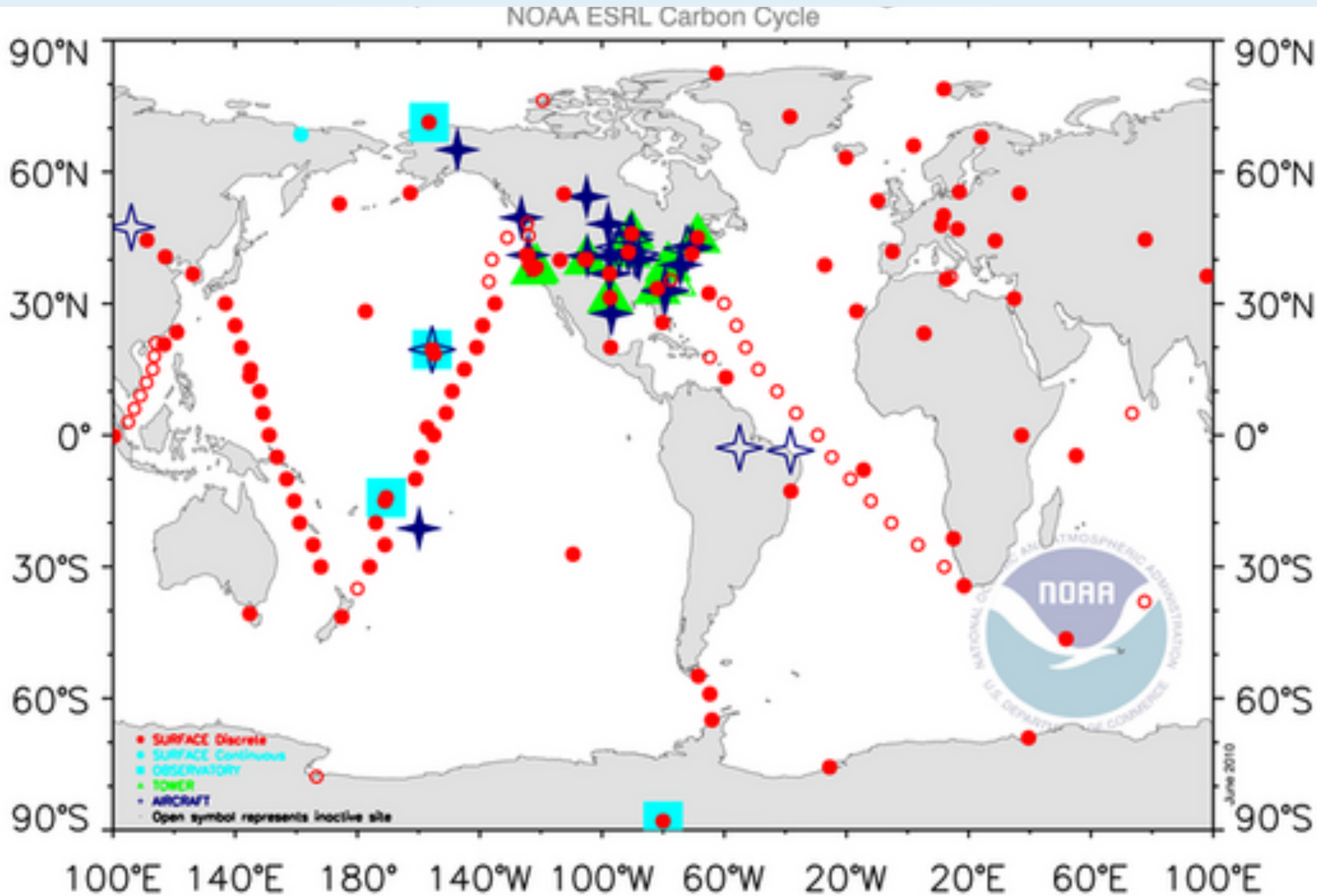
Three dimensional representation of the latitudinal distribution of atmospheric carbon dioxide in the marine boundary layer. Data from the GMD cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Contact: Dr. Pieter Tans and Thomas Conway, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6678 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

NOAA-ESRL

- ~ 100 sites at remote marine locations, bi-weekly flasks, 2m
- Long-term increase **2-3ppm/yr**
- Seasonal cycle ~**O(10 ppm)**
- N-S gradient **~ 1% of global mean**

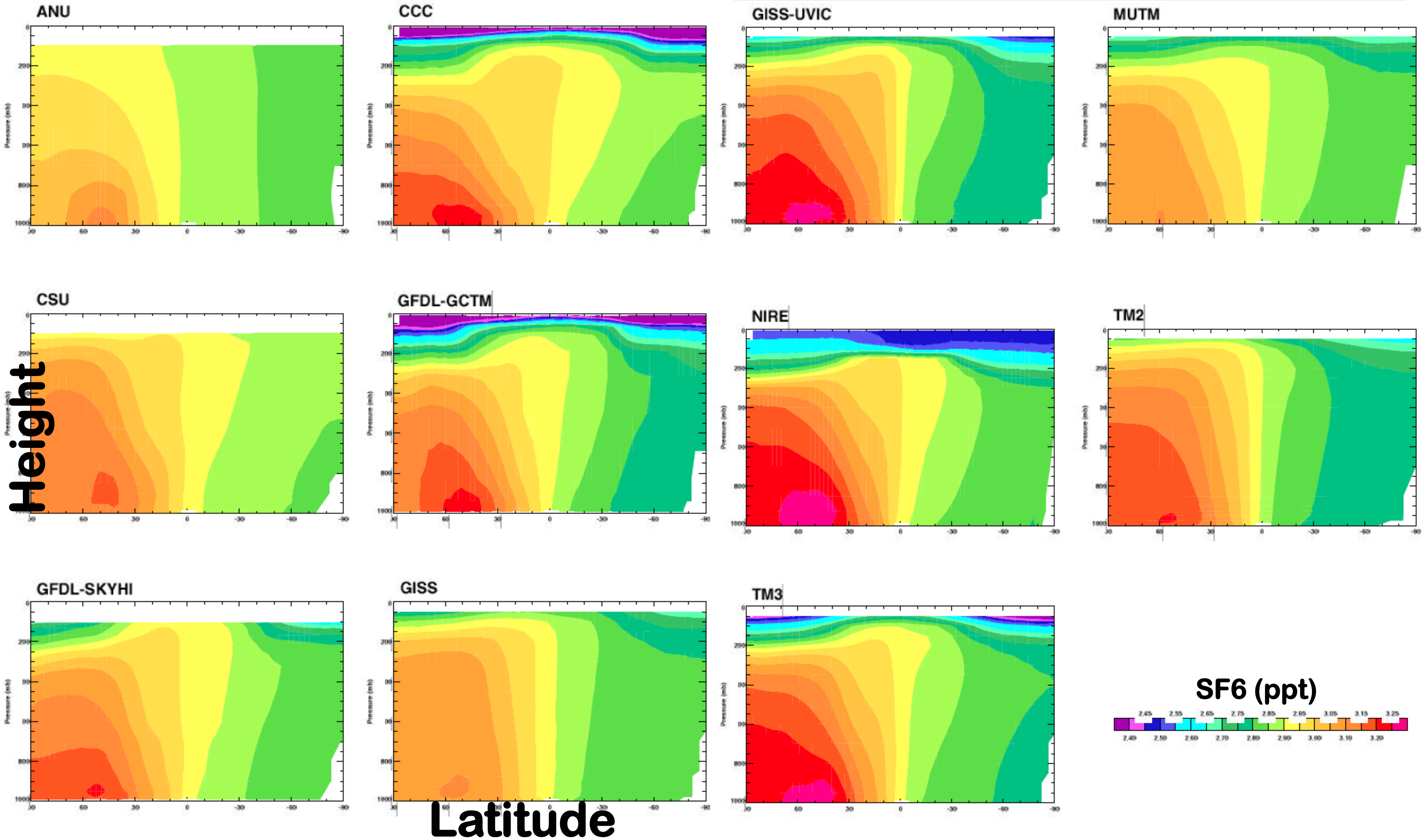


Current sampling in remote marine locations



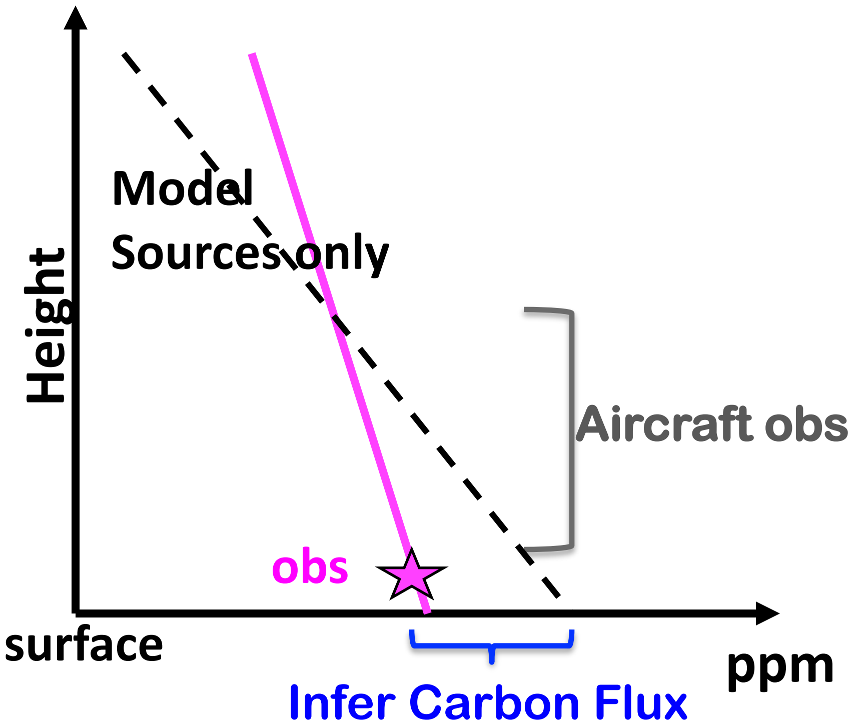
NOAA ESRL Carbon Cycle operates 4 measurement programs. Semi-continuous measurements are made at 4 baseline observatories, a few surface sites and from tall towers. Discrete surface and aircraft samples are measured in Boulder, CO. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, the stable isotopes of carbon dioxide and methane, and halocarbon and volatile organic compounds are measured. Contact: Dr. Pieter Tans, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

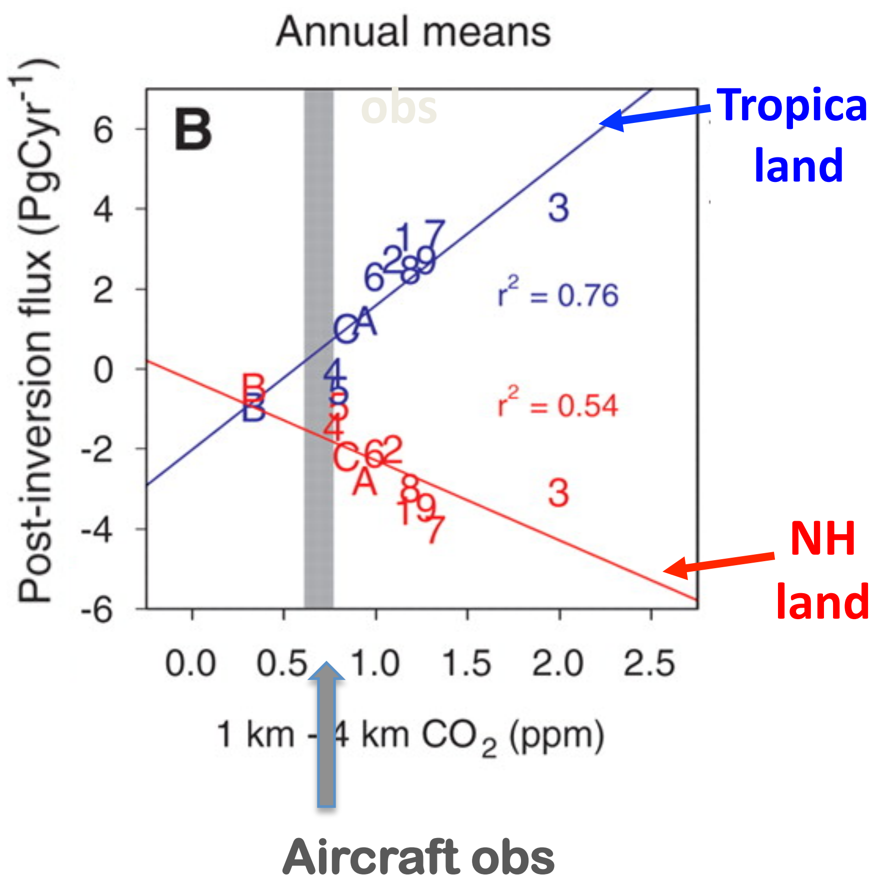
Inert Tracer: NH Industrial Source



Denning et al. Tellus 1999

CO2 Sink sensitive to CO2 vertical gradient





- Carbon Sink inferred as that required to match the observations;

Underestimate ←

→ Overestimate flux

Stephens et al., 2007, *(Science)*

Ensemble Kalman filter: application to carbon cycle data assimilation

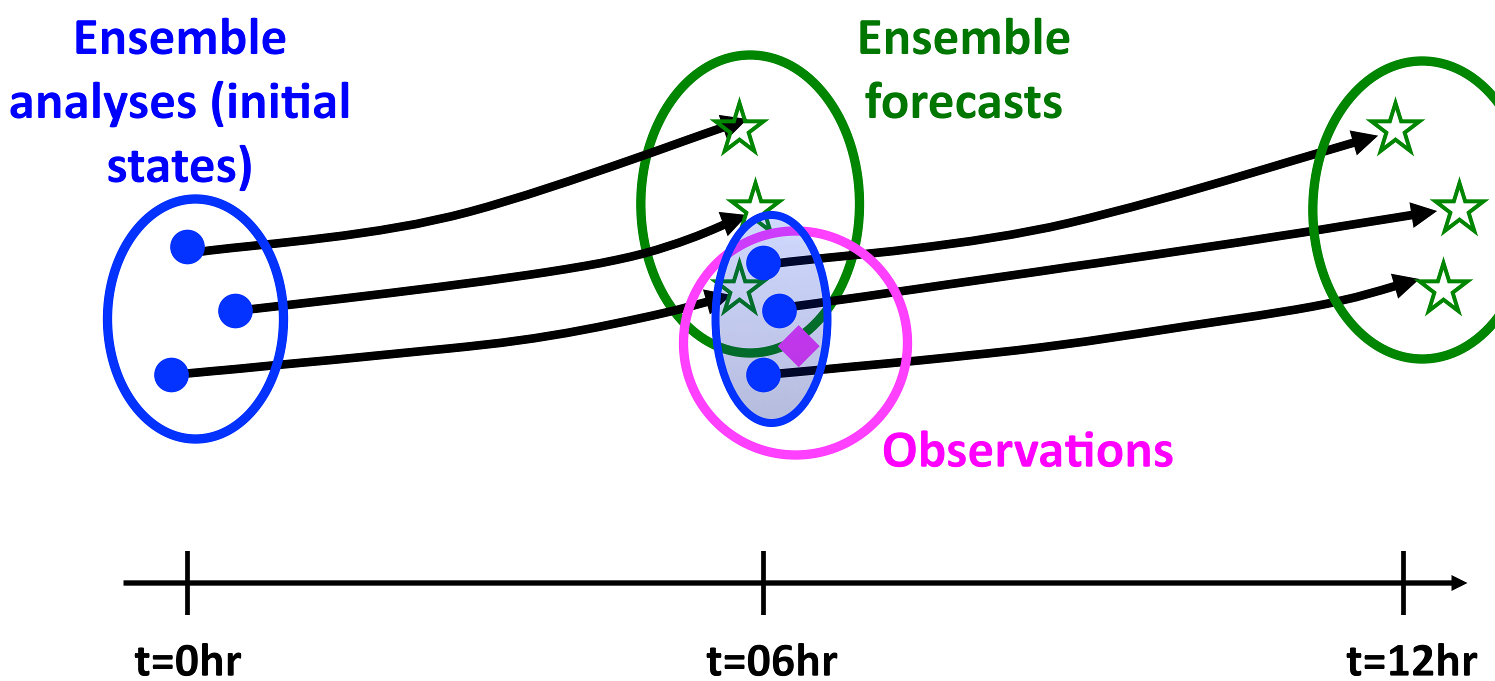
- Assimilate meteorological observations together with satellite and surface CO2 observations into a carbon-climate model
- Goals:
  - improve representation of carbon processes in carbon-climate model
  - Improve estimation of carbon sources/sinks
  - Articulate uncertainties in carbon sources/sinks due to uncertainties in transport

Junjie Liu, Inez Fung (University of California, Berkeley)
Eugenia Kalnay, Ji-Sun Kang (University of Maryland)

Supported by DOE

All the computations were carried out in DOE NERSC

Ensemble Kalman Filter (EnKF) process



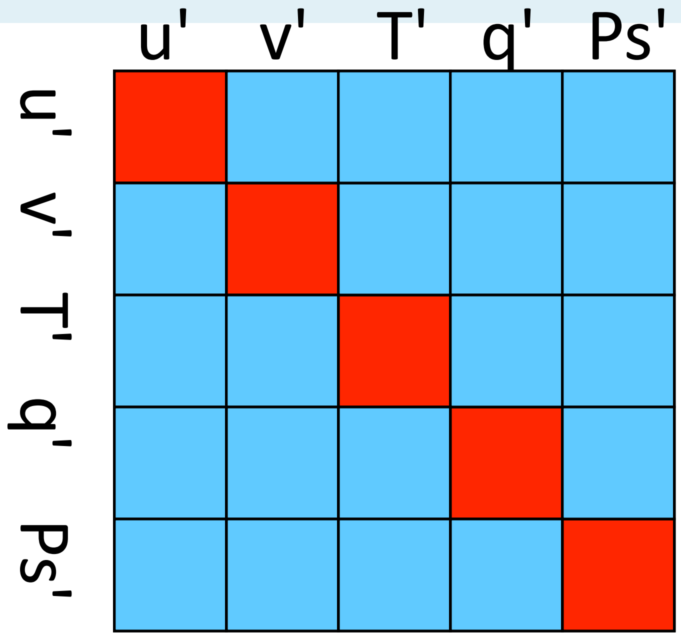
- Background error changes with time;
- Obtain ensemble analyses.

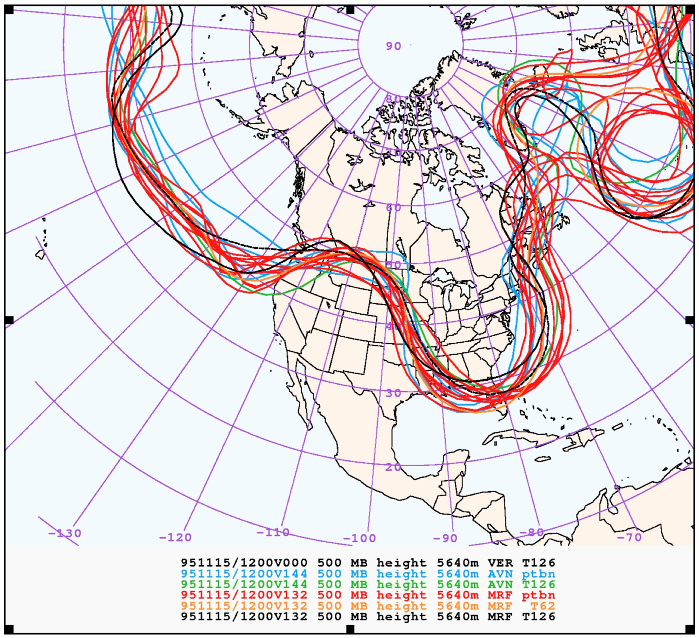
Forecast error statistics in EnKF

- **Run K ensemble members-> x_i^b; i=1..K**
- $\overline{\mathbf{x}}^b$ **: ensemble mean.**

$$\mathbf{P}^b = \frac{1}{K-1}\sum_{i=1}^{K}(\mathbf{x}_i^b - \overline{\mathbf{x}}^b)(\mathbf{x}_i^b - \overline{\mathbf{x}}^b)^T$$

$$= \begin{Bmatrix} u'u' & u'v' & u'T' & u'q' & u'Ps' \\ v'u' & v'v' & v'T' & v'q' & v'Ps' \\ T'u' & T'v' & T'T' & T'q' & T'Ps' \\ q'u' & q'v' & q'T' & q'q' & q'Ps' \\ Ps'u' & Ps'v' & Ps'T' & Ps'q' & Ps'Ps' \end{Bmatrix}$$





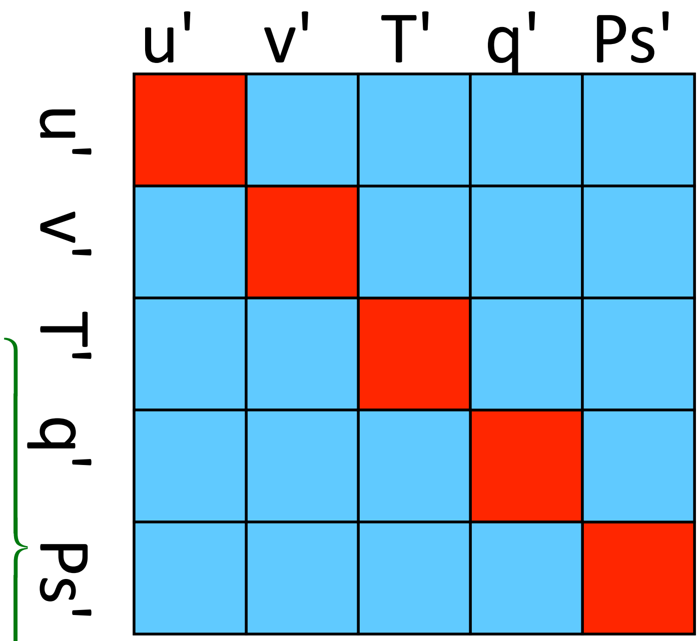
std dev in u' etc → error of the day
Large std dev → atm is dynamically unstable

Forecast error statistics in EnKF

- Run K ensemble members-> x_i^b; i=1..K
- $\overline{\mathbf{x}}^b$: ensemble mean.

$$\mathbf{P}^b = \frac{1}{K-1}\sum_{i=1}^{K}(\mathbf{x}_i^b - \overline{\mathbf{x}}^b)(\mathbf{x}_i^b - \overline{\mathbf{x}}^b)^T$$

$$= \begin{Bmatrix} u'u' & u'v' & u'T' & u'q' & u'Ps' \\ v'u' & v'v' & v'T' & v'q' & v'Ps' \\ T'u' & T'v' & T'T' & T'q' & T'Ps' \\ q'u' & q'v' & q'T' & q'q' & q'Ps' \\ Ps'u' & Ps'v' & Ps'T' & Ps'q' & Ps'Ps' \end{Bmatrix}$$



- Propagate info from the dynamical variables with observations to the dynamical variables with no observation.
- From location with observation to locations with no obs.

Summary steps of LETKF

1) Global 6 hr ensemble forecast starting from the analysis ensemble

2) Choose the observations used for each grid point

3) Compute the matrices of forecast perturbations in ensemble space X^b

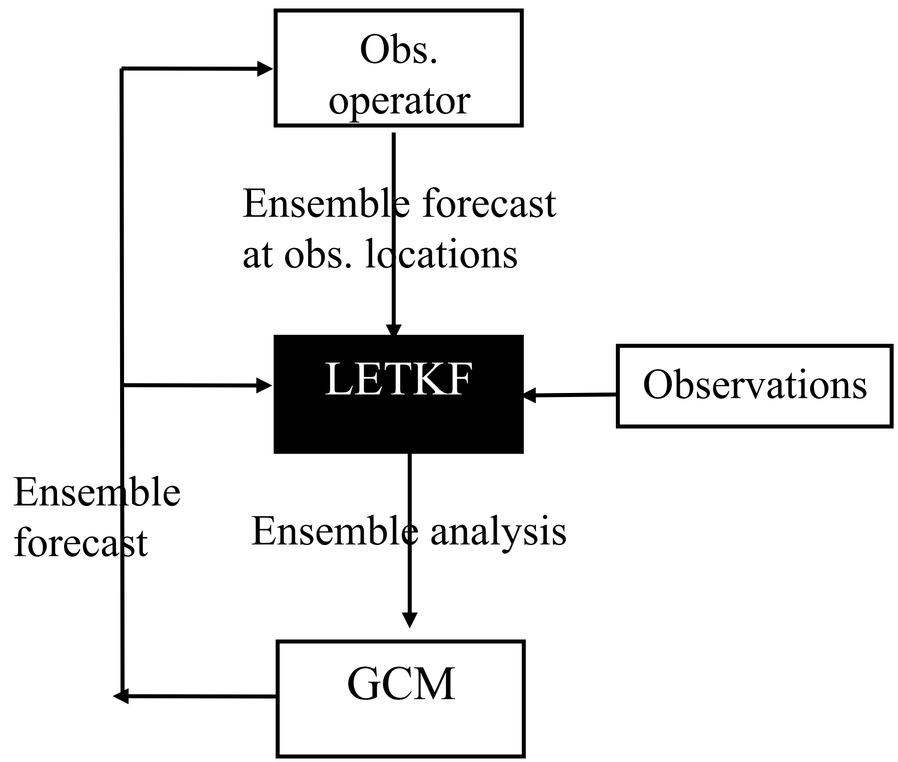
4) Compute the matrices of forecast perturbations in observation space Y^b

5) Compute P^b in ensemble space space and its symmetric square root

6) Compute w^a, the k vector of perturbation weights

7) Compute the local grid point analysis and analysis perturbations.

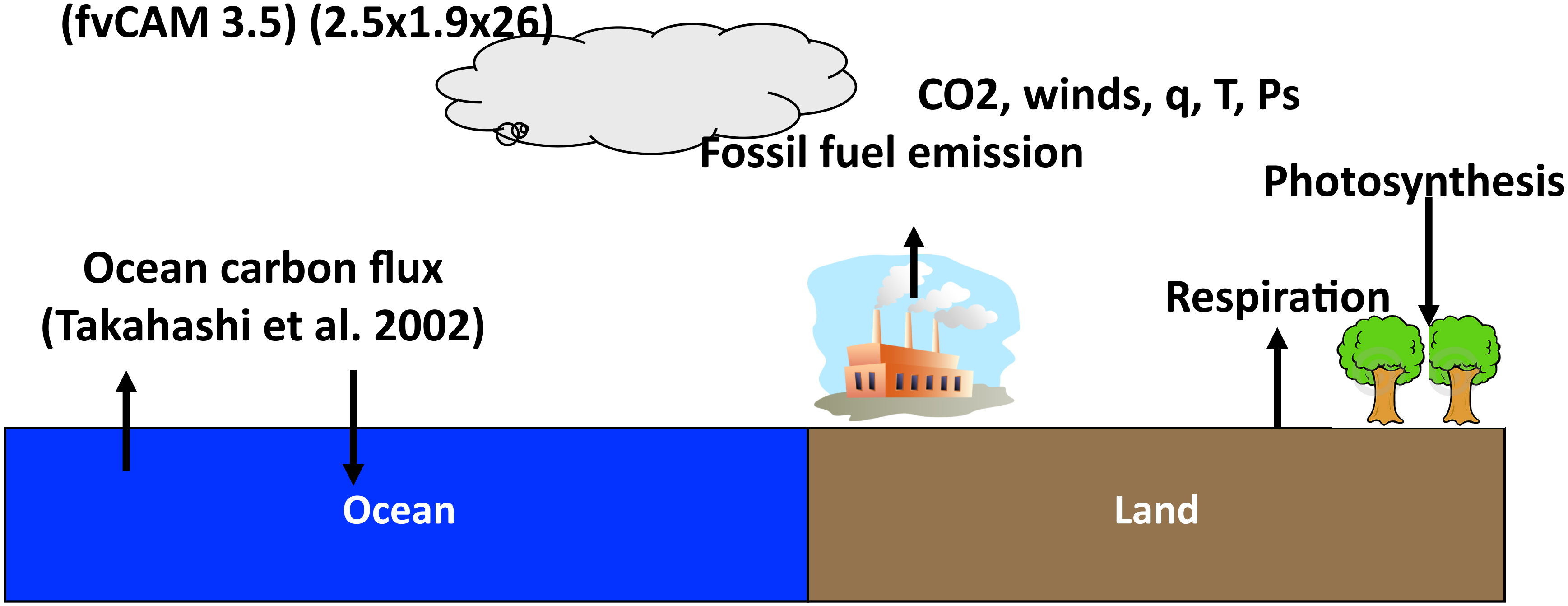
8) Gather the new global analysis ensemble.



DOE-NCAR Carbon-Climate Model

Community Atmospheric Model

(fvCAM 3.5) (2.5x1.9x26)

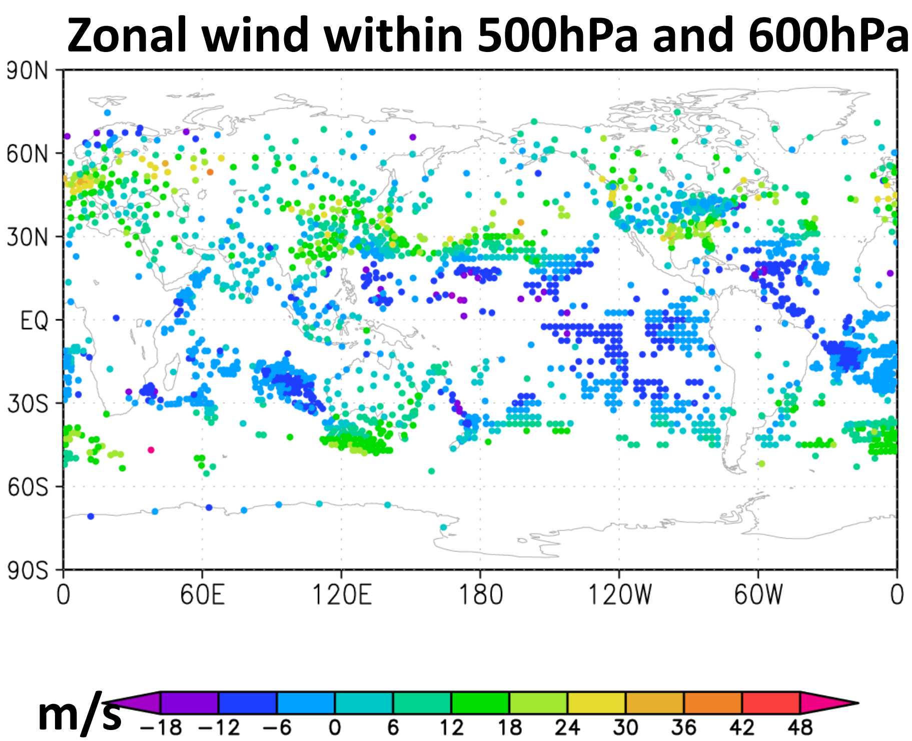


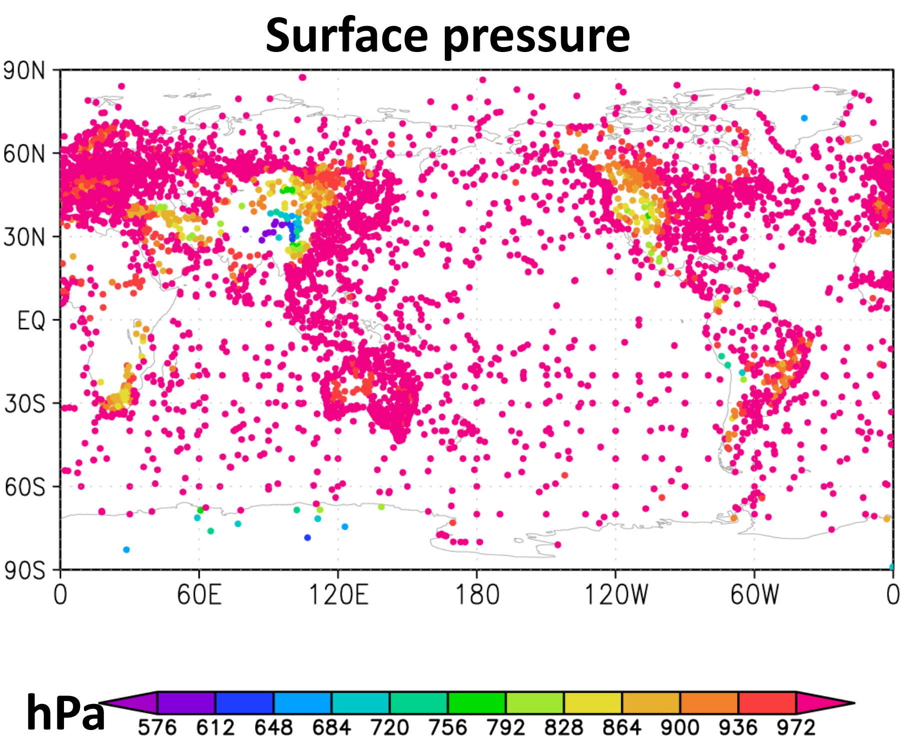
- **CO_2 is transported as a tracer in CAM 3.5.**
- **Land carbon flux: 6-hourly flux from biogeochemical model.**
- **Model produces CO_2 distribution that matches major features in surface CO_2 obs**
- **Time period: the first half year of 2003.**

The DATA

- **Raw Meteorology** every 6 hours: u, v, T, q, Ps
- **In-situ CO_2**: continuous near-surface CO_2 at Pt Barrow, AK; Mauna Loa; American Samoa; and South Pole
- **Satellite CO_2**: AIRS, ~100km, 2/day

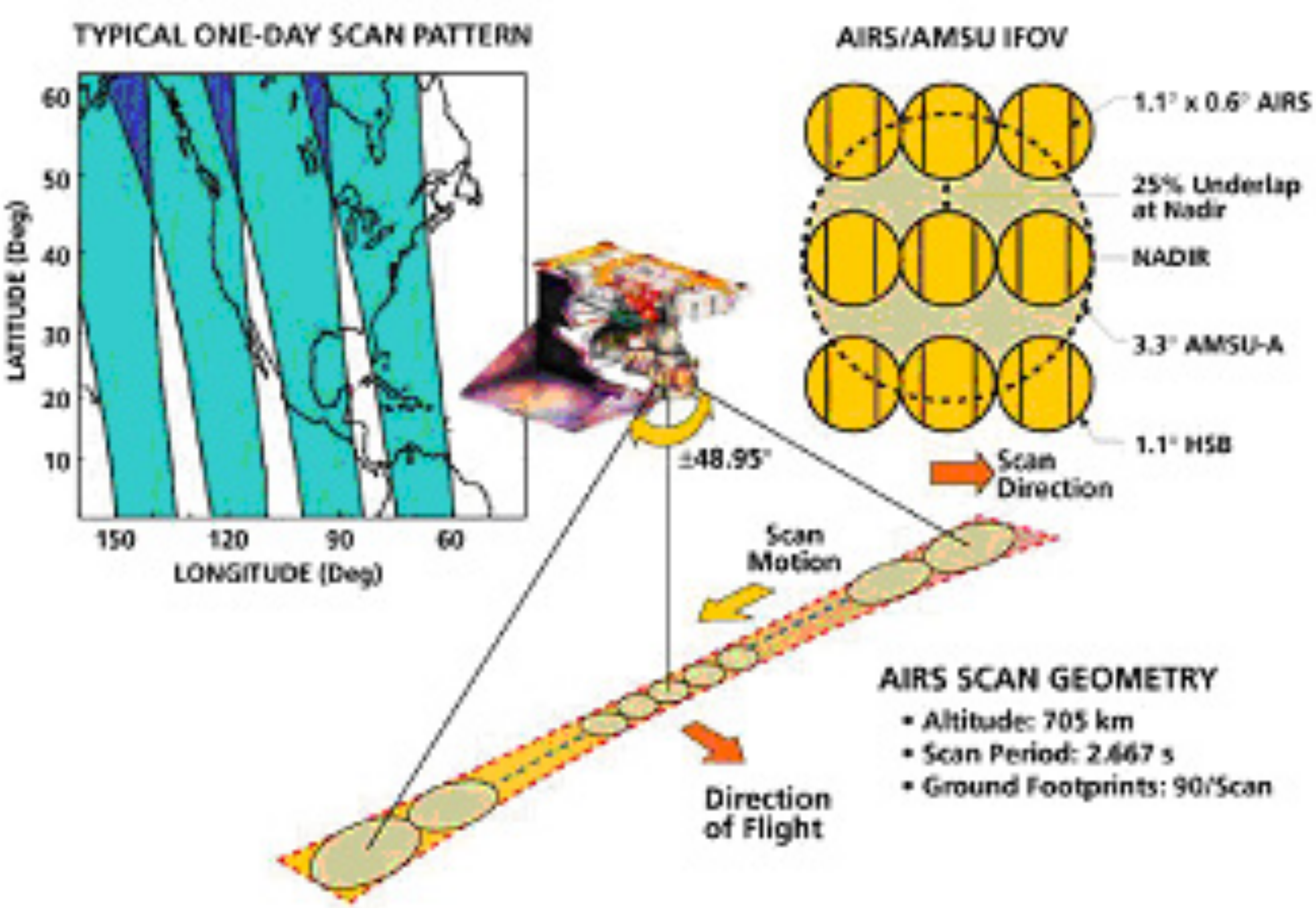
Meteorological observations include radiosonde, satellite, ships etc: examples





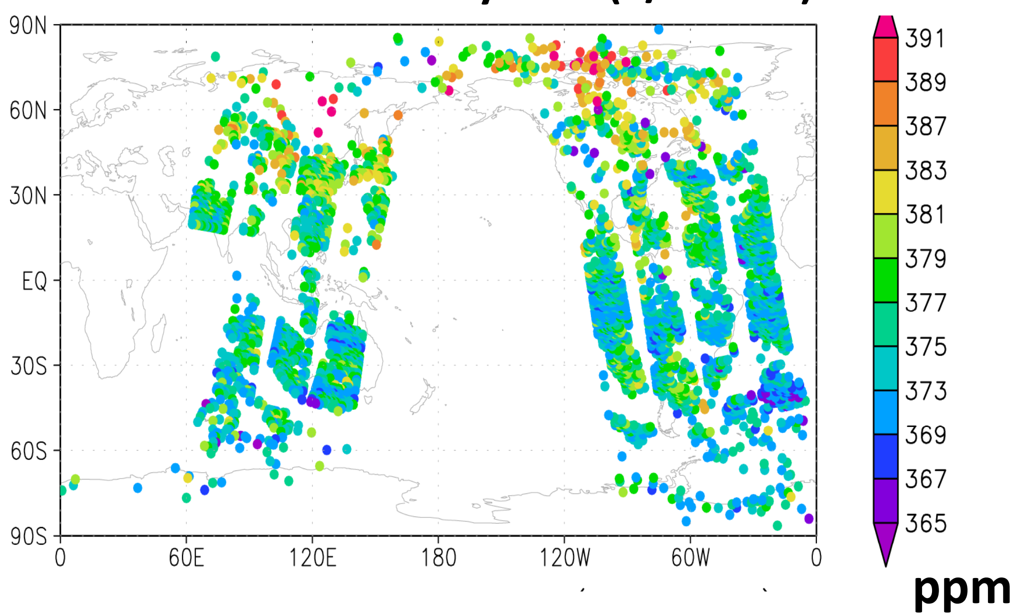
- Assimilate all the quality-controlled meteorological observations assimilated in the DOE/NCEP Reanalysis 2 products (Kanamitsu et al. (2002).
- 10^6 observations within 6-hour.

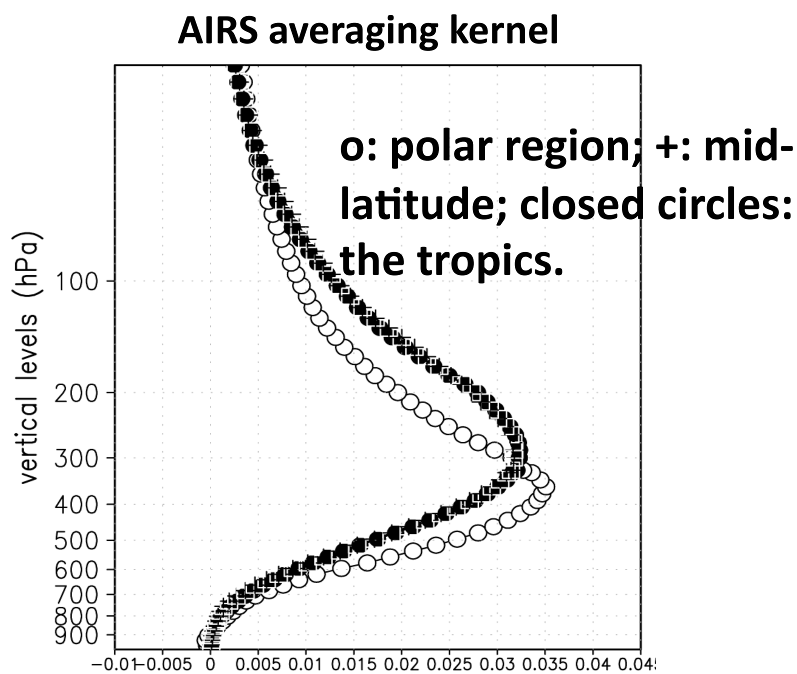
AIRS satellite instrument specification



- **Overpass the same spot twice per day;**
- **Footprint is about 100km.**

More than 2000 AIRS CO_2 within 6 hours; more sensitive in the middle troposphere



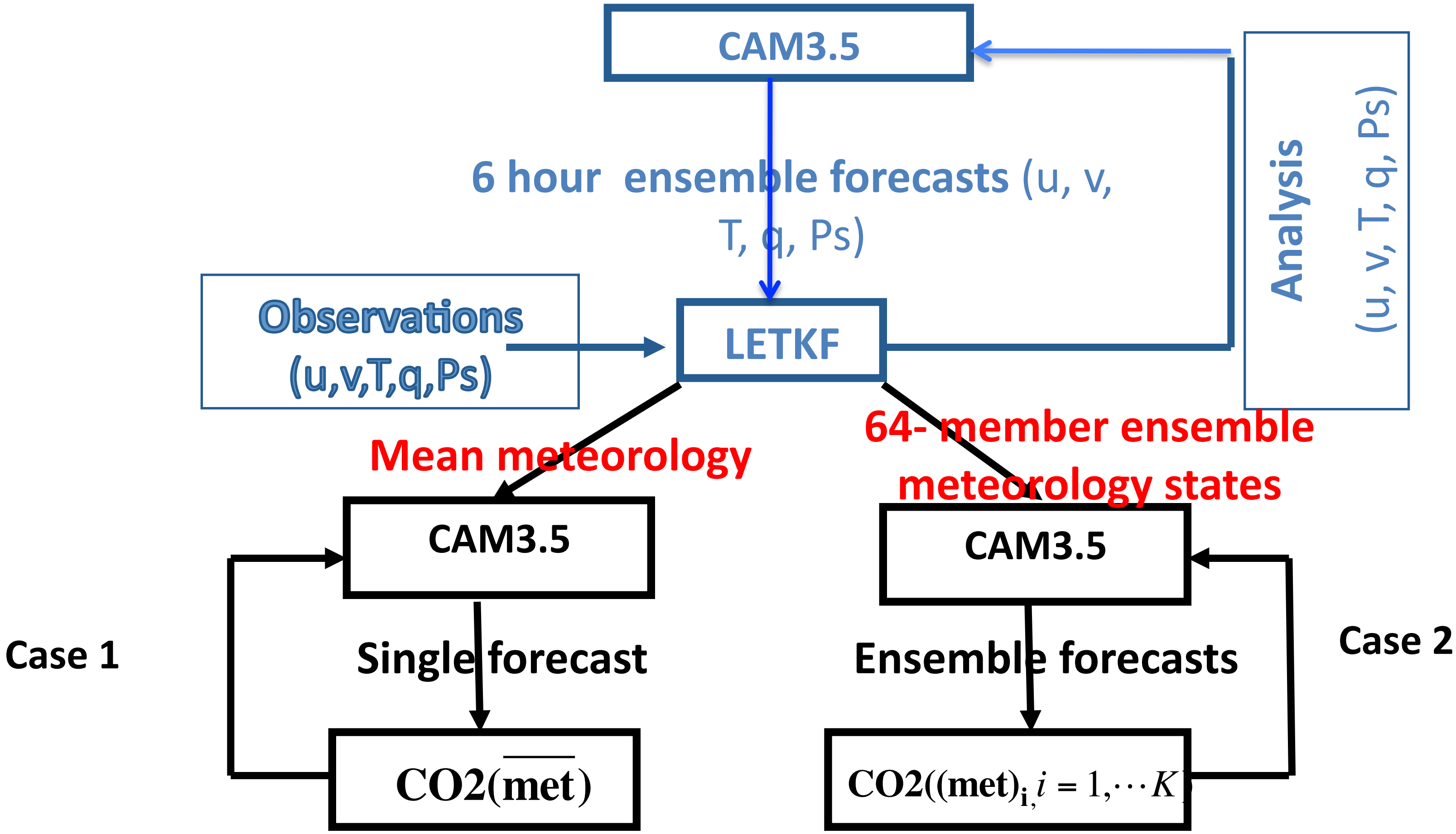


- **Averaging kernel: the sensitivity of AIRS CO_2 to the CO_2 at each vertical level.**

Assimilation Expts
(64 ensemble members)

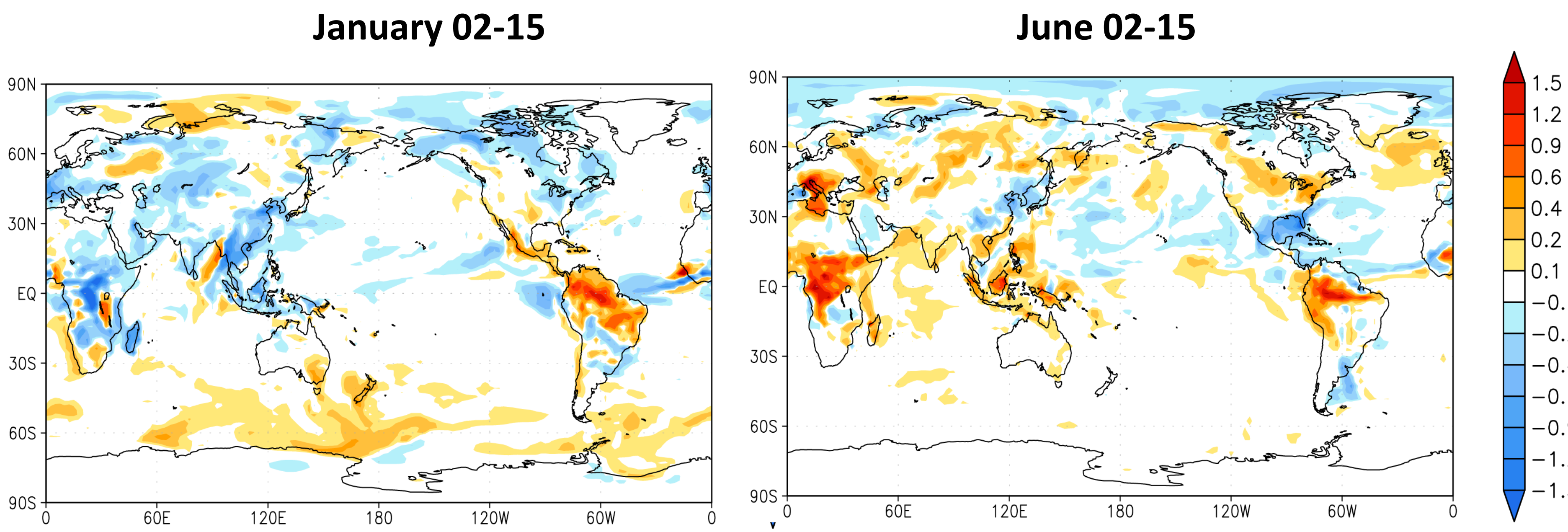
- Free run. No assim. CO_2 flux prior; CO_2 as inert tracer
- Met run: assim meteorology only. CO_2 flux prior; CO_2 is inert tracer
  - Compare with free run
  - Compare bias in CO_2 if use mean of meteorology
- Assimilate Met+CO_2; CO_2 flux prior (not updated)
- Assim Met+CO_2; update CO_2 flux

The impact of single and multiple meteorological states on CO2 forecast



BIAS from transport

$$[\mathbf{CO2}(\overline{\mathbf{met}}) - \frac{1}{K}\sum_{i=1}^{K}\mathbf{CO2}((\mathbf{met})_{\mathbf{i}})]\ \textbf{at surface}$$



- **Non-uniform in both space and time, with the difference as large as $\pm$1.5ppm.**
- **The difference is due to the nonlinear interaction in the model alone.**

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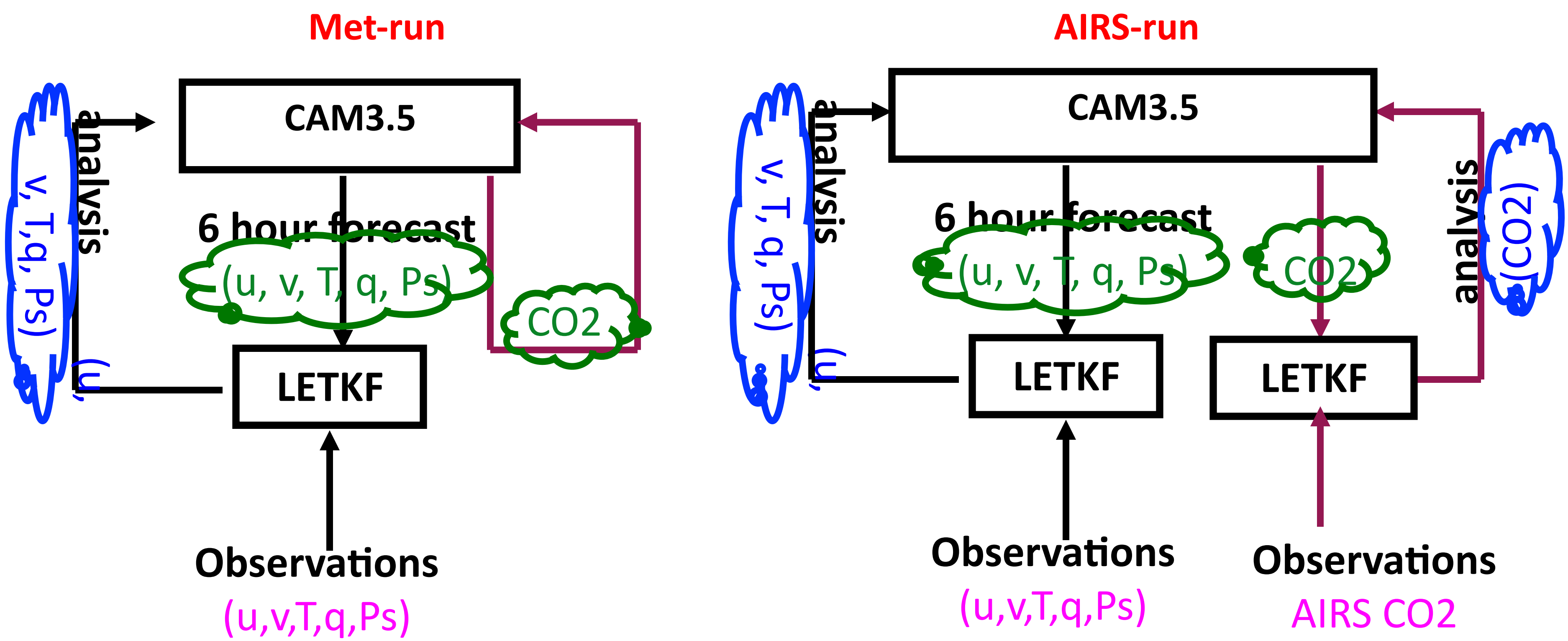
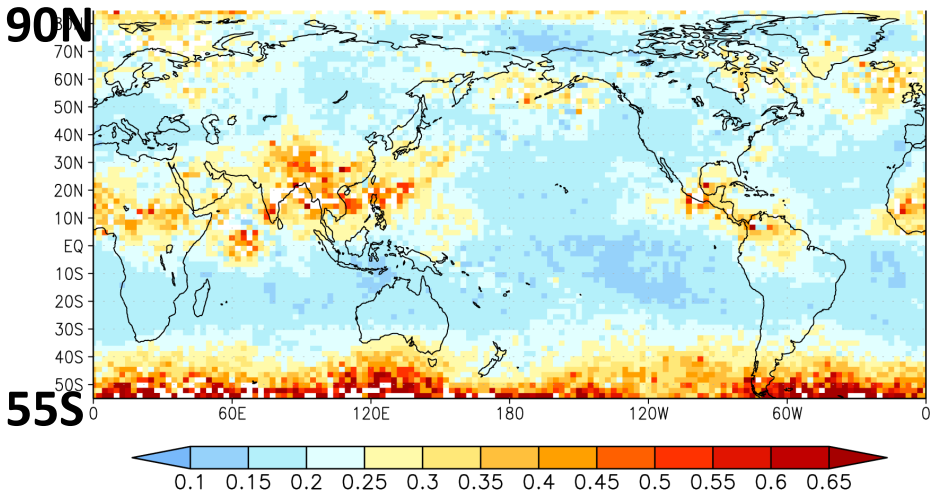
The impact of AIRS CO2 assimilation on 6-hourly CO2 3D (x, y, z) fields



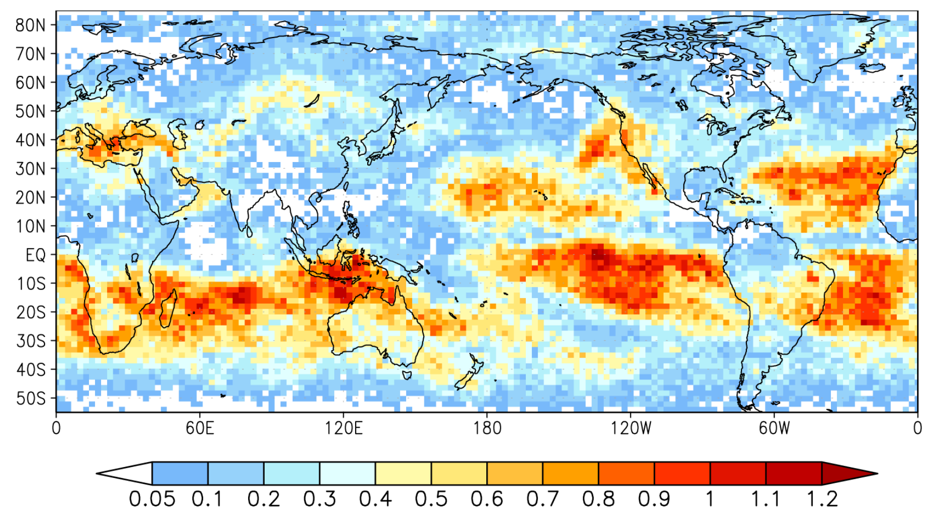
- AIRS-run: AIRS CO2+met obs; Met-run: only met obs.
- The first half year of 2003.
- Prescribed surface carbon flux forcing.

Relationship Between Analysis Ensemble Spread and Observation Coverage

CO_2 analysis ensemble spread at observation space



Average number of AIRS CO_2 observations within 6-hour



- **Analysis ensemble spread is anti-correlated with the the CO_2 observation coverage**

CO_2 at ~500hPa

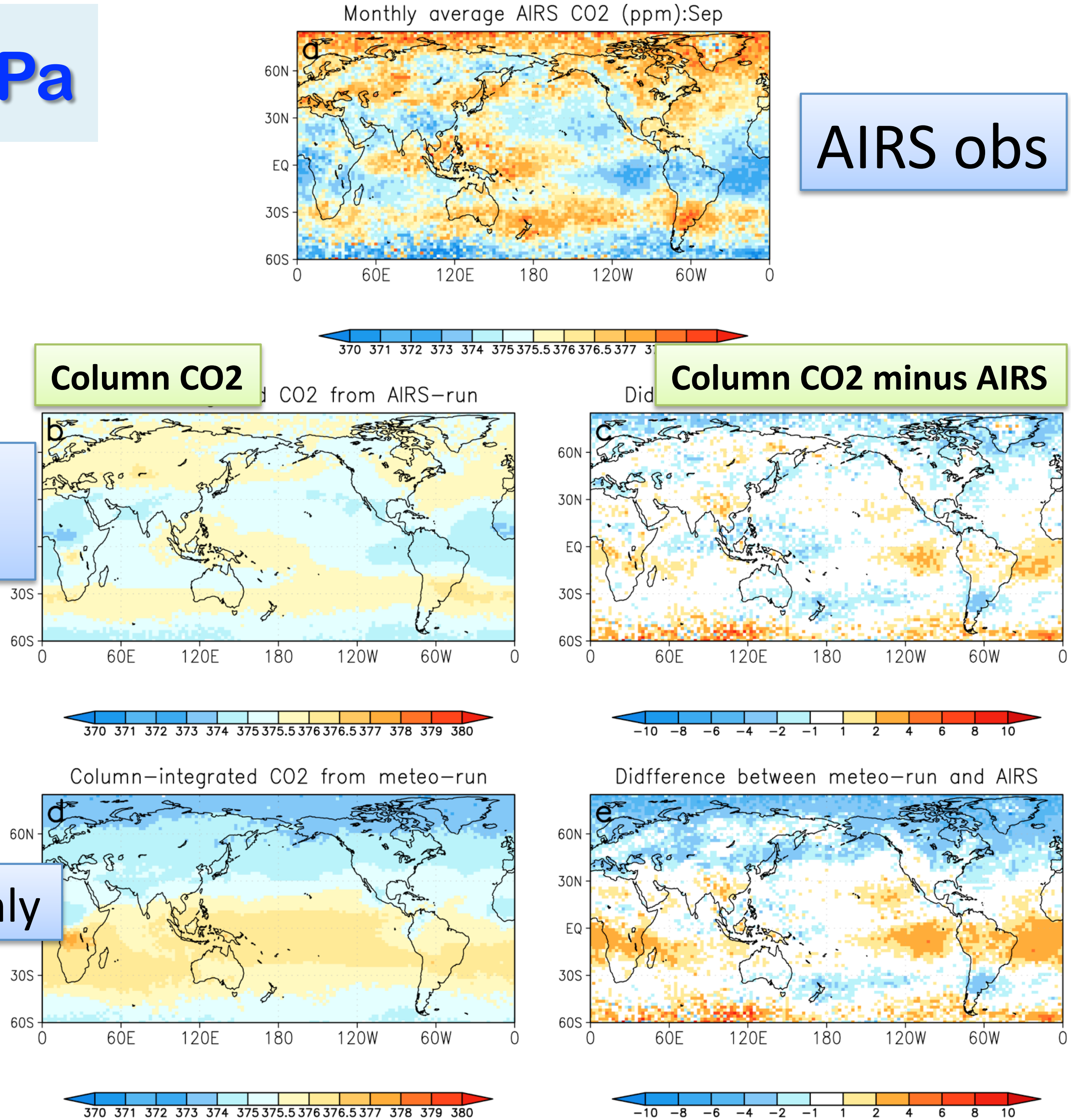
AIRS obs

Assim Meteorology +AIRS

Assim Meteorology only

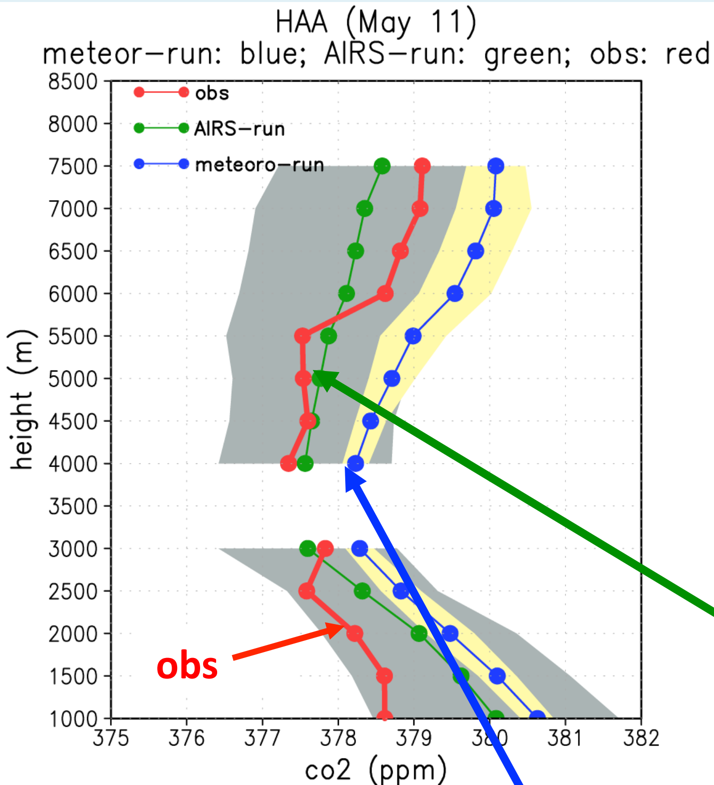
Column CO2

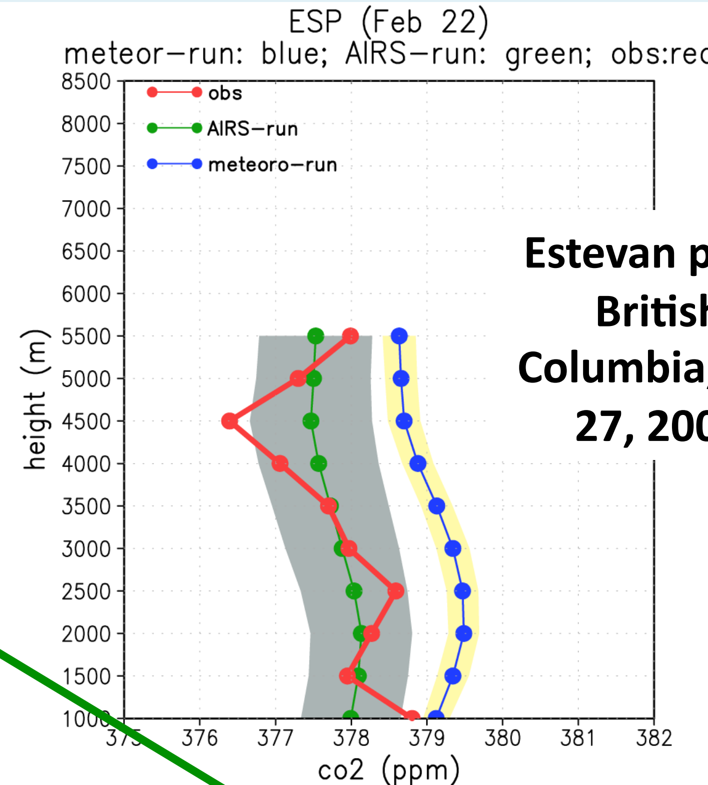
Column CO2 minus AIRS



Ensemble CO2 analyses bracket aircraft obs

Molokai Island, Hawaii. May 11, 2003





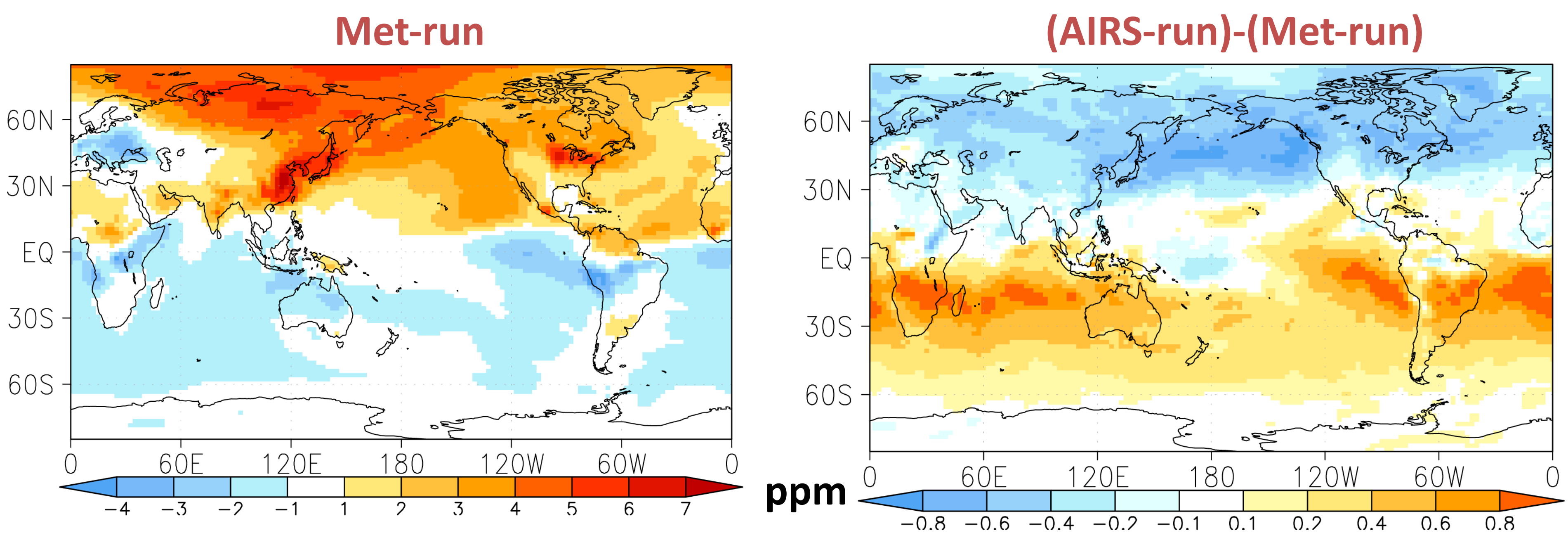
Estevan point, British Columbia, Feb 27, 2003

- Meteor-run: CO2 tracer transported by 64-member ensemble meteorological analyses generated every 6hr --> “precision” of CO2 “forecast” by model

- AIRS-run: CO2 assimilated along with meteorological obs.

Known: models underestimate vertical mixing

May 2003: CO2(925hPa)-CO2(500hPa)



- In the NH, CO2(925hPa)>CO2(500hPa): fossil fuel+ land carbon source;
- In the SH, CO2(925hPa)<CO2(500hPa): transported from the NH.

Assimilating AIRS CO2 decreases vertical gradient

Atmosphere

momentum

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \bullet \nabla \vec{u} + 2\Omega \times \vec{u} = -\frac{1}{\rho}\nabla p + g\hat{k} + \vec{F} + \boxed{\Im(\vec{u})}$$

energy

$$\frac{\partial T}{\partial t} + \vec{u} \bullet \nabla T = SW \updownarrow + LW \updownarrow + SH + LH + \boxed{\Im(T)}$$

water vapor

$$\frac{\partial q}{\partial t} + \vec{u} \bullet \nabla q = Evap - Condensation + \boxed{\Im(q)}$$

$CO2$

$$\frac{\partial C}{\partial t} + \vec{u} \bullet \nabla C = SfcFlux + \boxed{\Im(C)}$$

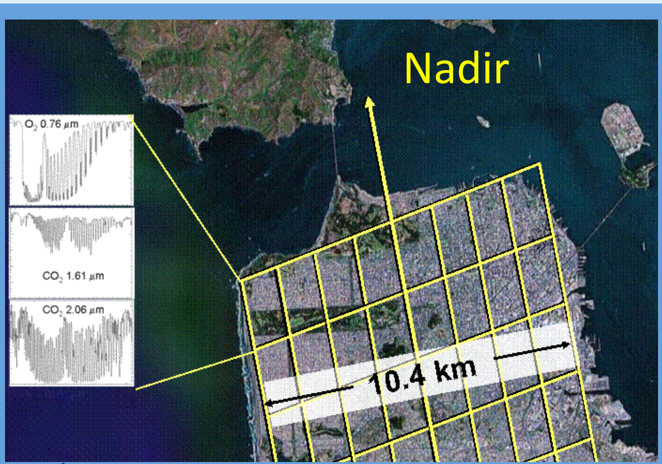
$\Im$ convective mixing

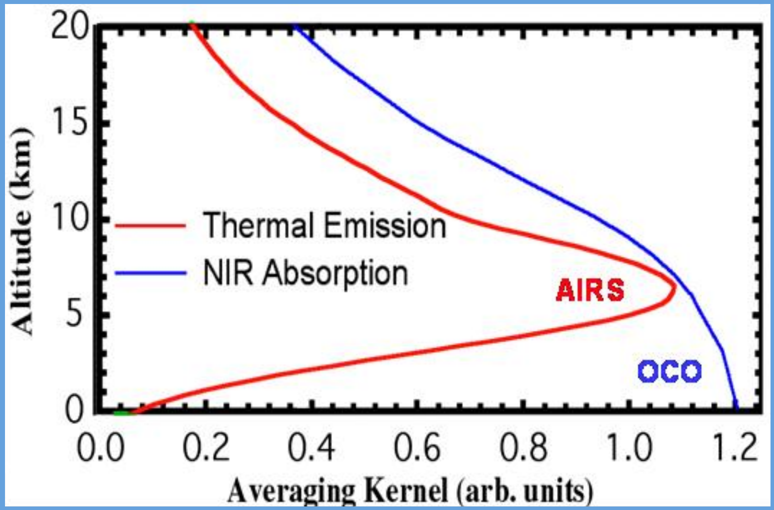
Sub-grid Scale Vertical Mixing

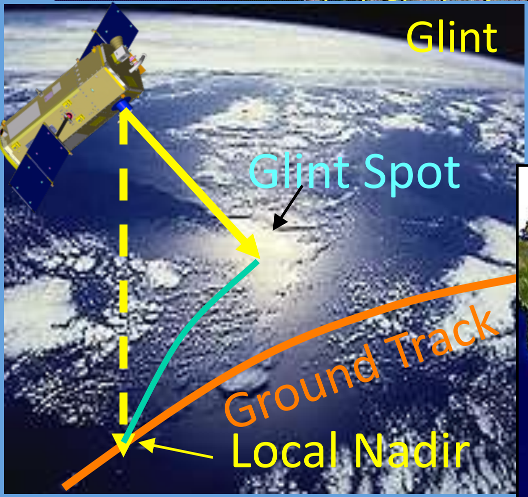
- **T(z), q(z) from meteorologoical assimilation ~= best approx to obs**
- **Convective mixing working terms on RHS of equations (in-situ source/sink terms) to produce "best" T(z), q(z)**
- **CO2 has no in-situ source/sink terms**
- **CO2(z) is a cleaner diagnostic of sub-grid scale vertical mixing**
- **CO2 is the only inert (in atm) tracer with repeating obs in the vertical**

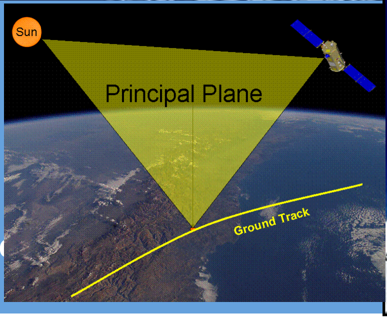
Outlook 1: Orbiting Carbon Observatory (OCO-2)

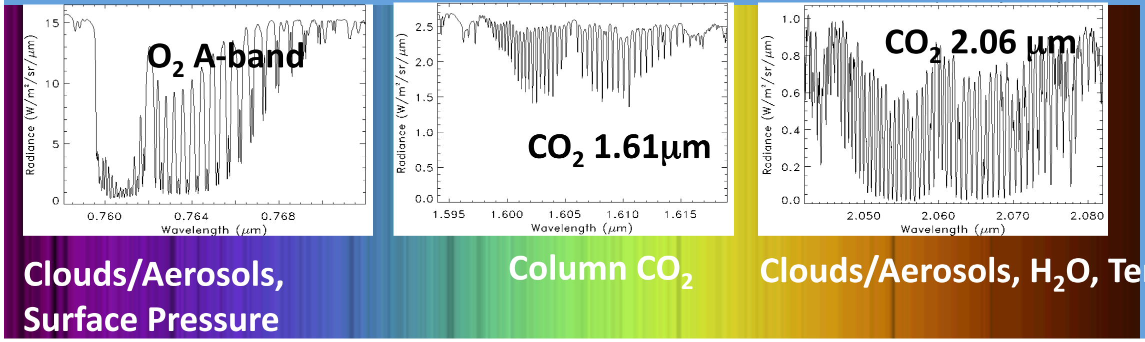
- High resolution spectra of reflected sunlight in near IR CO_2 and O_2 bands
- 3 km^2 footprint at nadir
- 3 Hz
- Sun-Synchronous Orbit (7km/s): 16-day repeat





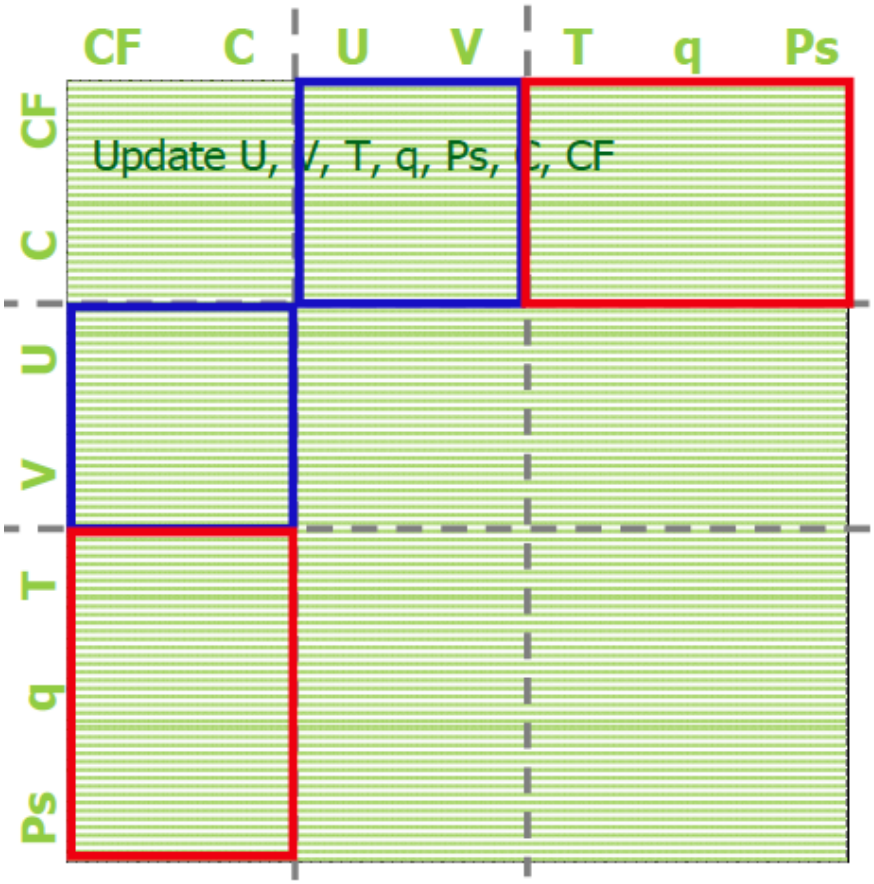






Outlook 2: Multi-variate Assimilation

Background Error Covariance Matrix, P^b



$$X^b = \begin{bmatrix} X^* \\ CF \end{bmatrix}$$

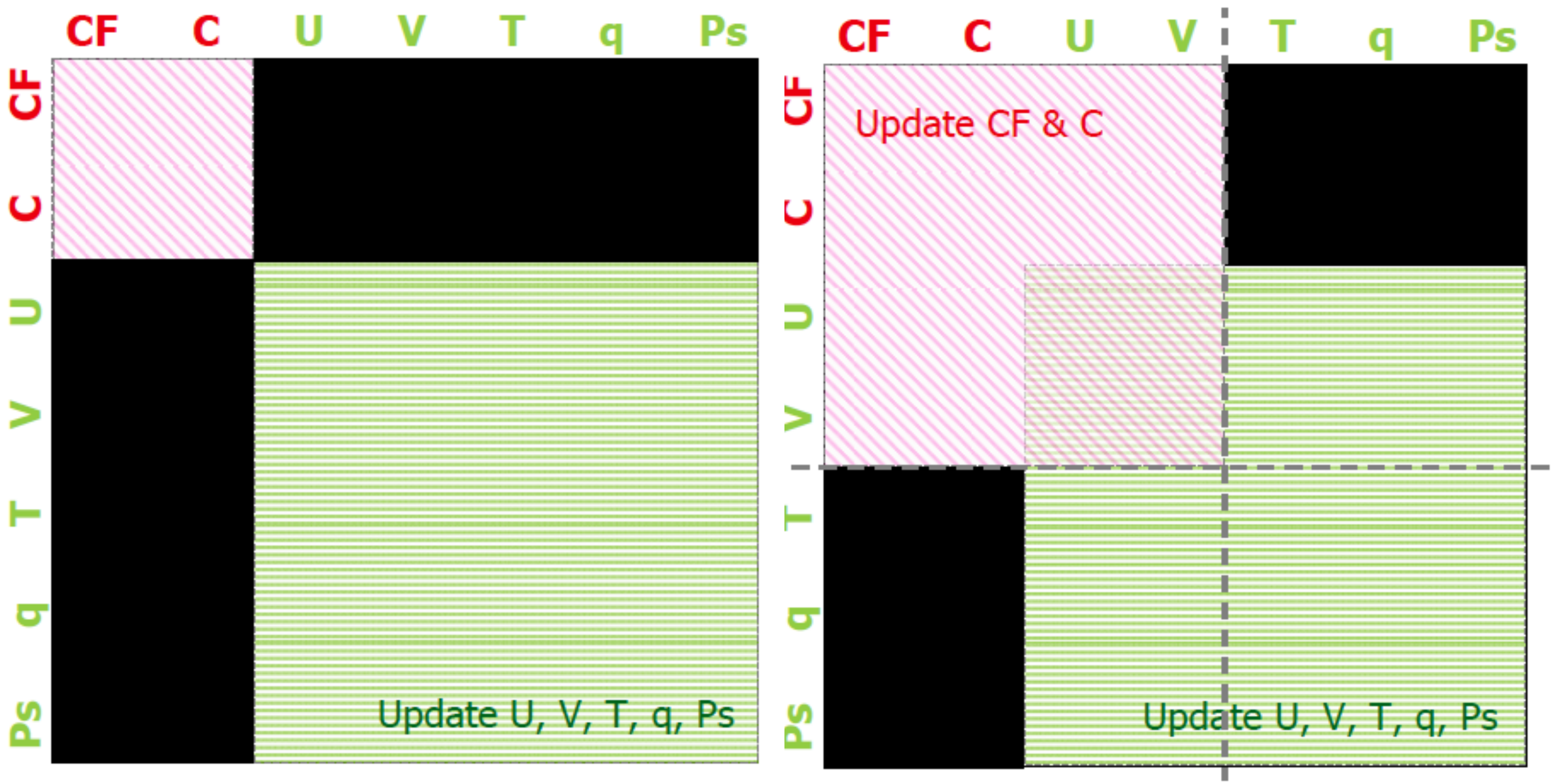
X^*=(U,V,T,q,Ps,C)

CF=surface carbon flux

- Errors of all variables are coupled
- Errors of CO_2 variables correlated with errors of all atmospheric variables (U, V, T, q, Ps)

→ This includes the error correlation between CO_2 variables and (T, q, Ps), which is not physical and introduces sampling errors

Ji-Sun Kang, PhD thesis 2009



CF C U V T q Ps
CF C U V T q Ps
Update U, V, T, q, Ps
CF C U V T q Ps
CF C U V T q Ps
Update CF & C
Update U, V, T, q, Ps